Chapter 2
Combustion of Solid Biomass: Classification of Fuels

Abstract The combustion of solid biomass and the classification of these fuels are considered. Firstly the different methods of combustion appliances and plants are outlined from a fundamental point of view. The forms and types of solid biomass fuels, their chemical composition and the way they are classified are then described. Characterisation by chemical analysis and instrumental methods are outlined.

Keywords Combustion methods · Classification · Chemical analysis

2.1 Methods of Utilisation

Biomass is unique as a renewable energy source because it can be used for all three energy sectors electricity, heat and transport. This puts a high demand on the resources available. Solid biomass fuels have the advantage that a wide range of materials can be used. This flexibility also applies to the methods used for biomass utilisation which can vary depending on the nature of the output, heat or electricity and on the size of unit required. Domestic appliances up to ~25 kW include open fires, simple stoves, household heating boilers and cookers—including traditional cook stoves used widely in developing countries. The use of biomass for heating has recently been widely promoted, especially in the EU. Modern biomass furnaces incorporate state-of-the-art design, but there are still problems associated with meeting NO_x and particulate emissions limits.

Many of the methods used for the larger scale utilisation of solid biomass are based on technologies developed for conventional fuels such as coal and lignite. These methods are described in standard textbooks on combustion technology (Speight 2013; Spliethoff 2010). They use technologies such as fixed bed combustors (up to 5 MWth), moving or travelling grate combustors (up to 100 MWth), fluidised bed (up to 500 Me), suspension firing/pulverised fuel (pf) combustion and co-firing with fossil fuels (up to 900 MWe). Many industrial processes such as biomass co-firing

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for power generation use only minor modifications to equipment designed for coal firing. This influences the pollutants formed.

Domestic heating is widely used throughout the world especially North America, Scandinavia, Europe and most Developing Countries. In Europe France is the largest consumer of wood for domestic heating, followed by Sweden, Finland and Germany. In the wintertime around half of all particulate organic matter in Paris has been attributed to biomass burning. Three methods available are open fires (up to 5 kWth), simple enclosed stoves, Patsari cook stoves and household heating boilers (3–10 kWth). Unlike larger units, these systems do not incorporate any flue gas after-treatment and as such emit significant particulate matter, unburned volatile organic matter and NO_x directly into the atmosphere. There is ongoing debate on the nature of these emissions from domestic applications as the rating of many units is based on steady state operation and does not take into account the initial start-up and refuelling emissions into account.

Pictures of typical small units are shown in Fig. 2.1, a typical African cook stove and an open domestic fire. The cook stove is insulated to improve its thermal efficiency.

Many design improvements aimed at improving the thermal efficiency of a system, such as improved air/fuel mixing and secondary air circulation will also reduce the pollutant emissions because the fuel will be burned more completely. But it is clear that the operation of a simple cooking unit or domestic stove will have a low efficiency and consequently high emissions from unburned fuel.

The basic features of a fixed bed combustor with fuel over-feed are shown in Fig. 2.2a. The main stages of combustion are shown but they do not occur in such a clearly defined sequential way in a real stove.

The fuel is added on top of the burning bed, consisting of logs, pieces of wood, briquettes, chips or wood pellets. The fuel undergoes devolatilisation forming carbon particles (containing ash), then these carbon particles react with CO_2 from the layer below producing CO, then the carbon particles falls to the oxidation zone forming CO_2 leaving ash. The ash, which will contain a significant amount of unburned carbon, falls through the grate and is removed periodically.

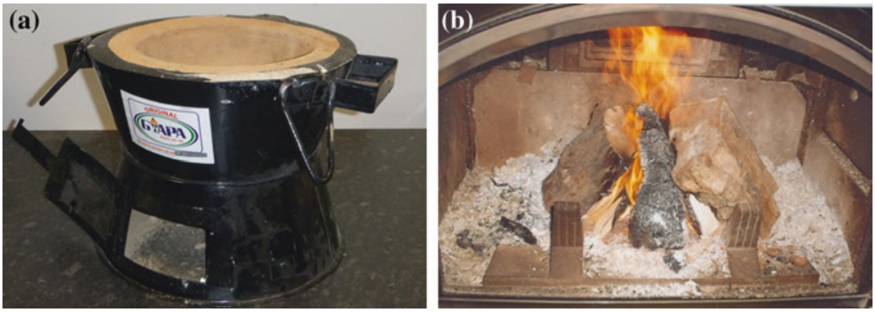


Fig. 2.1 Examples of domestic biomass combustion: **a** current technology cook stove, **b** domestic fire

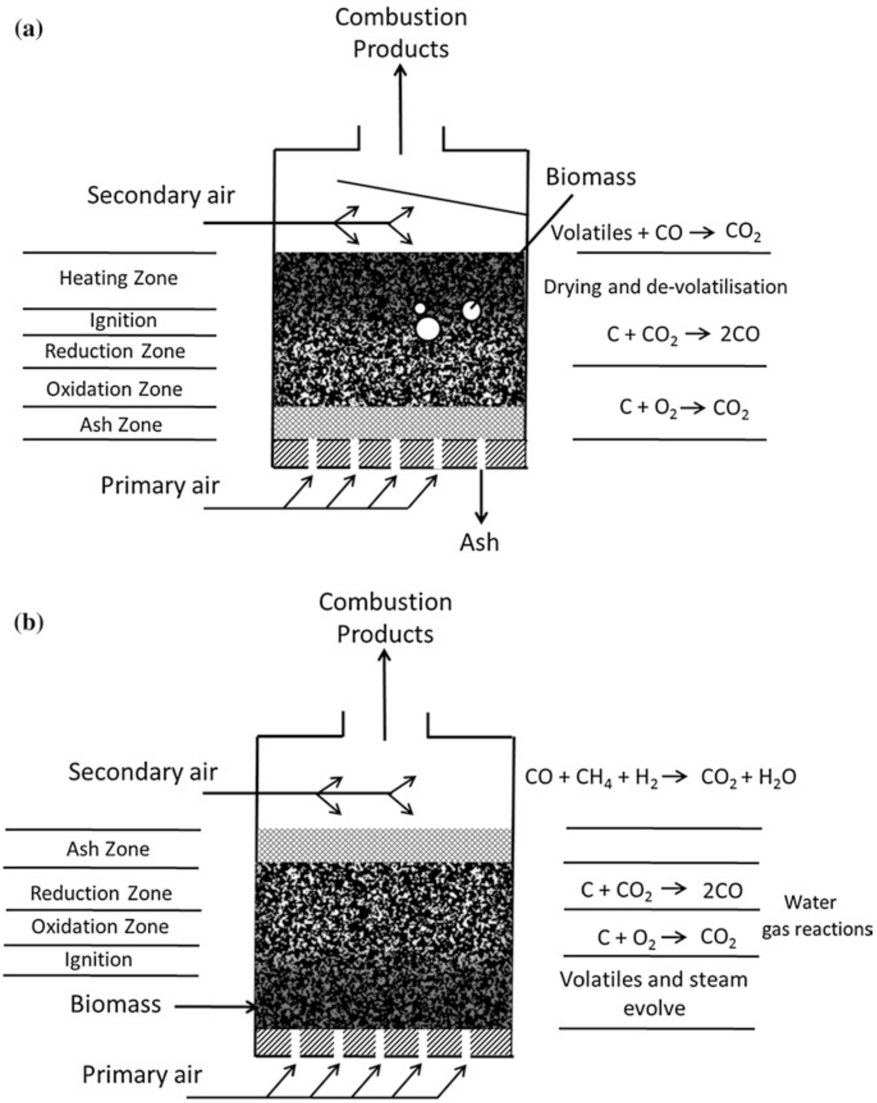


Fig. 2.2 **a** Idealised operation of a fixed bed combustor with over-feed arrangement. **b** Diagrammatic representation of an under-feed combustor

The problem with this type of combustor is that the smoke and unburned CO and volatiles escape from the top of the bed unless steps are taken to prevent that happening. In reality the movement of the particles leaves holes through the bed and so affects the air flow and hence the combustion process is not in a steady state. Most stoves in developed countries would have a deflector plate above the combustion region as shown in Fig. 2.2a so as to provide negative pressure in the flue to assist removal of the combustion products. The region above the deflector plate gives the opportunity for secondary combustion if secondary air is injected to permit the burn-out of soot and unburned hydrocarbons. However secondary air may be allowed to enter the furnace before that point by an inlet port or leakage as indicated in the figure. Stoves having a simpler design, such as cook stoves do not have this option of additional combustion air.

In larger domestic or commercial units (>30 kWt) a different method may be adopted in which the smoke and unburned volatiles are burned above the bed. This is the under-feed combustor shown in Fig. 2.2b. Here the unreacted volatiles and CO can react with the secondary air and their concentrations are reduced. Again such system would usually have a secondary combustion chamber above the bed and a flue.

Most industrial applications up to 100 MWth use either travelling bed combustion or fluidised bed combustion. Travelling grate combustors involve a continuously moving grate depicted in Fig. 2.3 but with the different stages taking place sequentially. A greater degree of burnout will take place but holes through the bed (called channelling) can take place. This type of combustor is widely used in incinerators as well as for biomass combustion because it can accommodate a wide range of feedstock sizes.

Fluidised beds are usually less than 100 MWth in size but some are built that can go up to 250 MWt depending on the availability of fuel. These systems consist of a combustion chamber into which combustion air is introduced via a perforated plate at the bottom with sufficient velocity that the bed of fuel and char above is fluidised. Because biomass produces about 90 % volatiles most of the combustion occurs above the bed. The bed thus consists of some char and an added particulate material such as sand. For fluidized-bed systems, the biomass fuels are pellets or chipped to 2–5 mm or larger which satisfy the fluidization requirements. They are particularly useful in that they can burn contaminated feedstock such as sewage sludge. A picture of a typical fluidised bed combustor plant burning wood and wood waste is shown in Fig. 2.4a. The combustor is situated in the main building surrounded by fuel handling and flue gas processing units.

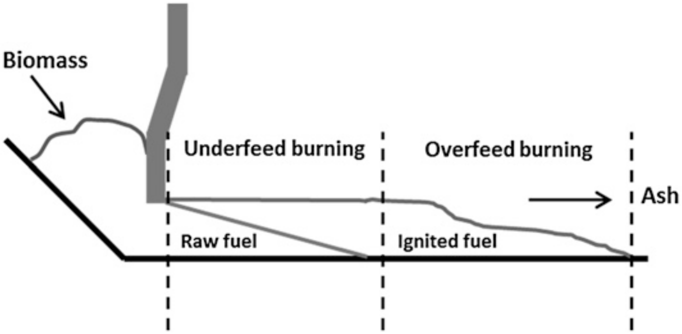


Fig. 2.3 Diagrammatic representation of a travelling bed combustor (not to scale—the length is shortened compared with a real unit)

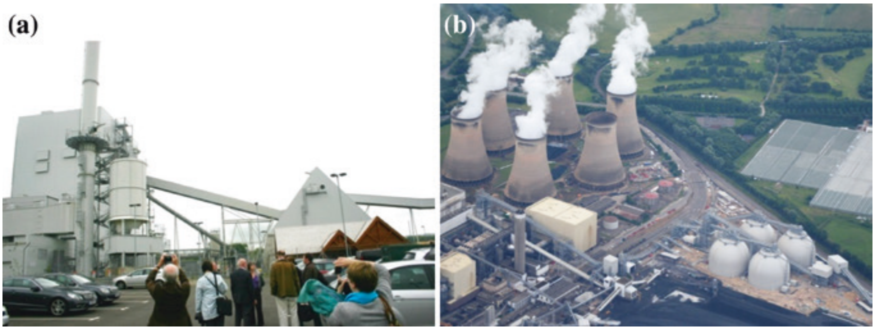


Fig. 2.4 Examples of industrial applications **a** 44 MWe bubbling fluidised bed combustion facility using wood, Stevens Croft, Scotland (power technology), **b** Drax Power Station, UK (Picture by AFT)

The industrial combustion plants consuming the largest amount of biomass in the world at present are used for the combustion of waste from paper and pulp manufacture (although much of this is black liquor) and from agricultural waste such as bagasse and palm kernel (IEA 2010). However an increasing application is for power generation by co-firing biomass with coal or near 100 % biomass firing in conventional power stations. An example of a large power station is Drax Power Station in the UK (4 GWe total capacity) which is shown in Fig. 2.4a. Large quantities of solid biomass fuels are used by co-firing with coal in such power stations; this may involve blending a proportion of biomass with the pulverised coal ranging from 3 wt% up to nearly 100 % biomass. This method of biomass utilisation gives high generation efficiency, extensive emission control equipment and therefore reduced emissions per unit of electricity. Energy from biomass is predictable and controllable so can provide base load demand as well as peak demand if needed. Two of the units at Drax are currently being converted to 100 % biomass firing and the new biomass storage domes are shown in the bottom right side of Fig. 2.4b.

Pulverised fuel (pf) or suspended systems use biomass fuel particles that are reduced to a wide range of 10–1,000 μm or more in order to accomplish complete burnout in typically a furnace residence time of 5 s. The biomass fuel usually has to be within a specified range of properties to ensure good combustion and to minimise slagging and fouling and corrosion in the plant. The technique of using milled biomass started because of the ease of milling a small amount of biomass with coal and burning it in the same boilers designed for pulverised coal combustion. The same furnaces and burners with staged combustion are readily used for co-firing with little adjustment. A typical staged pulverised fuel burner is shown in Fig. 2.5. Devolatilisation takes place in the primary zone under fuel rich conditions and the resultant mixture of char, gaseous volatiles and soot are burned out with the secondary air. Normally these burners have to use three stages to minimise the formation of NO. If the burners are using 100 % biomass then their design has to be modified in order to get stable flames.

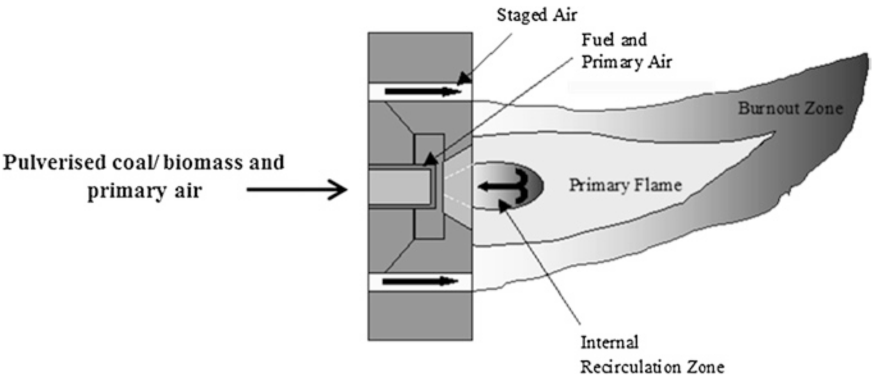

Staged Air
Fuel and Primary Air
Burnout Zone
Pulverised coal/ biomass and primary air
Primary Flame
Internal Recirculation Zone

Fig. 2.5 Diagrammatic representation of a low-NO_x staged burner

However most biomass does not mill as easily as coal because its fibrous nature results in poor grindability characteristics. This can result in larger particle sizes being produced, and increases wear on milling surfaces. This has implications for biomass handling methods. The effect on the times required for particle burn-out is discussed in Chap. 6. A comparison of a partially reacted coal particle and a partially reacted wood particle obtained using a scanning electron microscopy is shown in Fig. 2.6. The coal has melted so that the particle is nearly spherical and blow holes where the volatiles have escaped are dominant. In the case of the wood particle the remaining lignin is only partially melted and much of the original shape is retained at least initially.

Much of the handling technology for the larger units has been developed for coal or low grade fuels such as lignite and has now been adapted for biomass. There have been considerable efforts made to improve small units, but there are

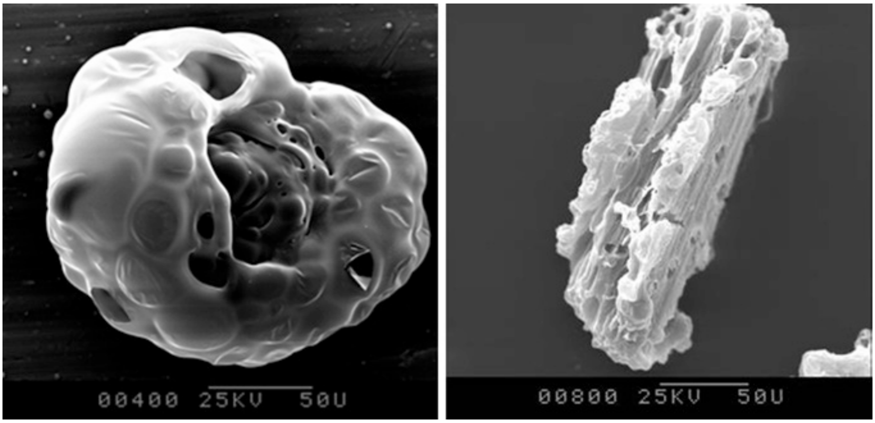


Fig. 2.6 Comparison of partially reacted fuel particle shapes (*left*) coal, (*right*) wood

inherent problems arising from their small size; these issues will be discussed later. Different biomass particle sizes are required for all these different systems, which impinge on the fuel supply and processing capabilities.

A further type of combustor that is available is the ‘flameless’ combustor where the flame temperature is about 1,000 °C and is not visible to the naked eye. This is a technique originally developed for the low NO_x combustion of gaseous fuels, but it has now been applied to the combustion of pulverised biomass (Abuelnuor et al. 2014).

2.2 Forms of Solid Biomass Fuels

The important issues are that there are multiple supply chains for solid biomass fuels, multiple applications, different scales of implementation, and a lack of an established infrastructure and standards. As a consequence it is not easy to generalise on the forms of solid biomass fuels on a global basis.

The UK Biomass Strategy identified the following biomass resources (DEFRA 2007)

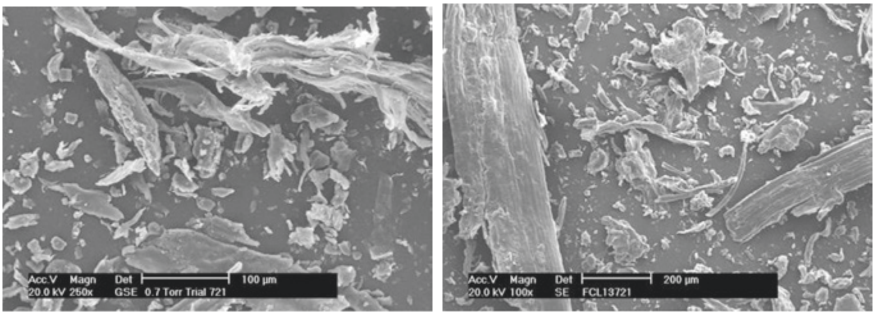
- Conventional forestry
- Short rotation forestry
- Sawmill conversion products
- Agricultural crops and residues
- Oil bearing plants
- Animal products
- Municipal solid waste
- Industrial waste

The main sources of biomass are wood, energy crops and agricultural wastes. The most promising energy crops include Miscanthus, short rotation willow (SRW) and reed canary grass (RCG). Wastes include wheat straw, recycled waste wood in Europe and North America, bagasse, Palm Kernel and Olive wastes from the countries where these crops are grown.

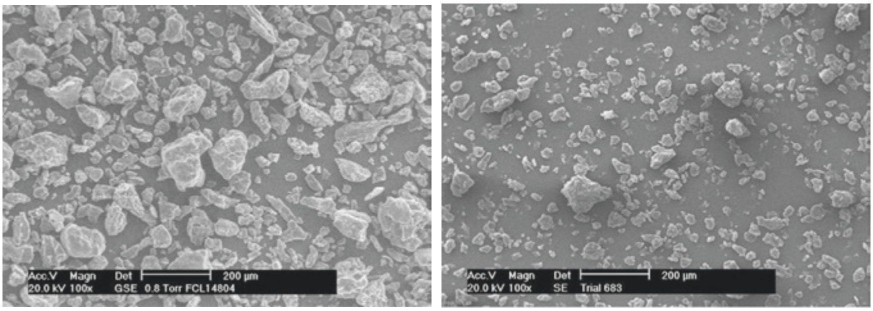
The motivation for using biomass is to reduced greenhouse gas emissions, and so the sustainability and life cycle analysis of biomass supply should take into account emissions of all GHG including CO_2, N_2O and CH_4. Farming methods involving application of large amounts of fertiliser or clearing large land areas might increase net Greenhouse Warming Potential, GWP (Smith et al. 2012).

Some biomass materials such as agricultural residues may be used directly, but in the case of small appliances they first have to be made into pellets or briquettes. Solid biomass fuels are available in a variety of forms. These include logs and straw, and also processed products such as chips, pellets and pulverised fuels mainly from wood, straw and a range of agricultural residues. Logs are generally available in three standard sizes (25, 33, 50 cm), which fit the combustion chamber geometries of commercial log boilers. Similarly, wood chip standards [CEN/TS 14961: 2005 (E)] have been introduced in the EU to standardise properties such as dimension, moisture (range from dried to about 20 % moisture which can be stored, ash and nitrogen, and to provide information on heating value, density and chlorine content. In the case of pellets the standard [CEN/TS 14961: 2005 (E)] specifies the same properties: dimensions (based on diameter and length), moisture, ash, sulphur, mechanical durability, fines, additives, nitrogen. Information on heating value, bulk density and chlorine content are also recommended. There is a variety of chipping, grinding and pellet-making machines and, in the latter case, this often involves the capability for a certain degree of drying. In pellet making small particles (2–5 mm) of the biomass are compressed whilst steam heated and the lignin present acts as a binding agent although a binder can be added. Pellets are now an accepted form of fuel for many smaller units and since they can easily be transported and stored they are used as a fuel for pf power stations where the pellets are milled to provide the necessary particle size.

Direct firing of pulverised biomass or the co-firing with coal requires particles that are ground to less than 1 mm in size. Comminution of fibrous materials is difficult and expensive in terms of both energy and money because of the strength of the fibres present. Fibrous biomass requires about 5 times the energy of bituminous coal, however the process of torrefaction (van der Stelt et al. 2011; Basu 2013) can modify the nature of the products making it easier to mill. Torrefaction



Milled wood Miscanthus



Olive waste PKE

Fig. 2.7 Different biomass types illustrating the particle types resulting from milling

is the term used for roasting coffee and a similar process is used for biomass-it is heated at about 290 °C for about 30 min during which time much of the hemicellulose is lost, the degree of torrefaction being determined by the reaction conditions. Torrefied biomass has a higher energy density and if used for pf combustion grinds to smaller particles more readily. It also has advantages for use as a fuel for bed combustion. Agricultural process residues including nut products, such as Palm Kernel Expeller (PKE), and olive waste are available in ground form and are less fibrous than woods and grasses. The contrast between these different fuels the fibrous materials, wood (SRC, short rotation willow coppice) and straw, and the easily ground fuels, olive waste and PKE, is shown in the Fig. 2.7.

2.3 Types of Solid Biomass Fuels and Their Classification

As is the case with conventional fuels large data bases on the properties have been developed of which the most extensive is Phyllis 2 (2014). Proximate analysis is used to characterise biomass in order to measure its moisture, volatile matter, fixed carbon and ash contents. Ultimate analysis gives the actual chemical composition (usually C, H, N, S and O by difference). The metals content is also determined. Care has to be taken in the way in which these results are expressed and can be on as received basis (ar), dry basis (db), or dry ash free basis (daf). Values for the Higher Heating Value (HHV) are also obtained, this term is usually employed by the power generation industry but other terms used are calorific value or enthalpy of combustion. Details of these techniques are given in standard procedures which are available as CEN, BS, ASTM, NREL, Japanese and Chinese Standards. These methods of analysis were originally designed for use with coal and adapted for use with biomass, for example, by reducing the furnace temperature from 815 to 575 °C for the ash measurement, which avoids losses of volatile alkali metals. Some of these techniques developed for wood and straw are not necessarily applicable to some oriental biomass species with high protein content (Rabemanolontsoa et al. 2011).

Conventional solid fossil fuels are classified by a range of standard tests which are determined by a number of considerations. The commercial 'value' of a fuel as determined by the Higher Heating Value, volatiles, ash content and similar parameters is important, but so are safety considerations (flammability characteristics, biohazards etc.). Technically there are other criteria that determine the mode or ease of transportation or ease/efficiency of use in the end application (e.g. density, hardness, particle size). Finally, environmental factors (S, N contents) are also important. It should be noted that wood is a major feedstock for the paper industry and there are a wide range of standards for this industry which can sometimes be applicable to combustion. In particular the ratio of cellulose/lignin criterion is important in paper making, as are the methods of their measurement.

Until recently solid biomass fuels were not traded internationally on a large scale commercially and application was limited to the combustion of wood, logs, specialist applications of industrial waste from sugar cane bagasse, palm olive and from paper manufacture. Most of the applications were for domestic heating and cooking. The developments in the last decade of biomass on a large industrial scale have prompted the use of more rigorous standard test methods for not only combustion but also in handling and safety. These include safety in transportation and storage such as fire and biological hazards, the mechanical handling pellets or torrefied products and particularly friability and fine dust formation.

Difficulties arose came from the wide diversity of biomass feedstock, and a need exists for a comprehensive classification system which covers both physical and chemical specifications. The ultimate aim of such a system would be to allow the user to predict the behaviour of a biomass feedstock through its classification, preferably based on a few simple tests. Properties of biomass, which are important for combustion purposes, include pyrolysis behaviour, tar yield, volatile composition, together with the yield and composition of the char and its reactivity towards oxygen. Also, the inorganic composition is much more variable for biomass compared to coal, and this impacts on the combustion behaviour and needs to be considered. Clearly, measuring all these properties for each biomass feedstock is time-consuming and unrealistic; one aim is to consider the application of suitable correlations between them.

Biomass material can be broadly classified into groups based on the general assessment of their source. The major groups in this way shown here in Table 2.1 are (i) woody: pine chips, an energy crop, willow, (ii) herbaceous: two energy crops are listed—Miscanthus and Switchgrass, (iii) agricultural residues: wheat straw, rice husks, palm kernel expeller, bagasse (a sugar cane residue), olive residue or olive cake (the waste from olive oil mills), and animal wastes such as cow dung. Data for lignin and cellulose samples are also given in Table 2.1 for comparative purposes (the latter is an exact quantity but the value for lignin depends on the type of lignin). This broad classification is represented by examples in Table 2.1 together with analyses which are taken from the Energy Research Centre of the Netherlands (ECN) online data base, and information on a wide range of materials can be obtained from that compilation. It should be noted that the composition of many of these materials can vary depending on a number of factors, such as time of harvest, soil type, geographical location. The woods consist of two types, hardwoods and softwoods, the former are from deciduous trees (e.g. willow) and the latter from evergreens (e.g. pine). Typically the composition (wt%, dry basis) for hardwoods is: cellulose, 40–44 %, lignin 18–25 %; softwood, cellulose 40–44 % and lignin 25–35 %. The chemical nature of the hemicellulose and lignin are different. In hardwoods the hemicellulose consists of 10–35 wt% xylan whilst in softwoods the xylan content is 10–15 wt% and a major component is water soluble galactoglucoannan. Lignins consist of hydroxyphenylpropane units (described in the next chapter) and their content in hardwoods is 7–11 wt% and in softwoods it is 13 wt%. As already pointed out there is considerable variability of composition even in the same stem and between different trees.

Table 2.1 Typical proximate (db, %) and ultimate analyses % (daf) and higher heating values for a range of biomass types

Fuel (Oven dried)	Proximate analysis, db			Ultimate analysis, daf				HHV
	VM	FC	Ash	C	H	O	N	MJ/kg (dry)
Wood pine chips	80.0	19.4	0.6	52.1	6.1	41.44	0.3	21.02
Willow, SRC	83.4	15.01	1.59	51.0	6	42.9	0.1	18.86
Miscanthus giganteus	82.1	16.4	1.5	49.4	6.4	43.93	0.3	19.88
Switchgrass	82.94	14.38	2.69	47.52	5.96	44.8	0.37	19.07
Straw-wheat straw	71.89	17.8	10.32	46.35	6.29	47.92	4.04	18.18
Lignin	74.57	22.03	3.4	53.0	5.9	39.74	1.11	22.20
Cellulose	88.3	10.96	0.74	43.62	6.55	49.67	0.2	17.38

Source Phyllis 2 (2014)

The herbaceous biomass fuels and the agricultural fuels can be significantly different from the woods in terms of the trace metal and nitrogen contents and which have a significant bearing on the pollutant formation as described later.

2.4 Characterisation by Chemical Analysis

The data in Table 2.1 was obtained by chemical analysis which plays a major role in the understanding of the combustion behaviour of biomass. The major components are measured using the same analytical methods devised for coal although nitrogen and ash present a problem. Fuel-nitrogen can be difficult to measure because it can be in low concentrations necessitating the use of special methods. Ash can contain volatile components that prevent some of the older coal analysis methods being used as previously described.

All biomass contains the nutrients nitrogen, phosphorus and potassium and the other major essential elements are Ca, Mg, Na and Si, while minor species include Mn, Fe, Mo, Cu, and Zn. Chlorine is also present. A considerable amount of information is available about these species because they can have a very significant influence on slagging, fouling, corrosion in the furnace as well as pollutant formation. The single most important species is potassium. Straw would contain typically large amounts of potassium/chlorine: 0.2–0.97 dry% Cl and 0.7–1.3 % K; whilst woods would contain smaller amounts of potassium/chlorine: typically <0.1 % Cl and 0.2–0.5 % K. Silica tends to be a main component in the ash of herbaceous crops and residues (straws as well as rice husks), while calcium is higher in woods and some of the herbaceous energy crops. Detailed analyses of the C, O, H, N, S, Cl constituents have been given by Vassilev et al. (2010) and by Vassilev et al. (2013) for the inorganic constituents.

The simplest method of classification is based on chemical analysis. A method has been that suggested by Chen et al. (1998) which parallels the type of approach adopted previously for coal classification systems. This classification is based on

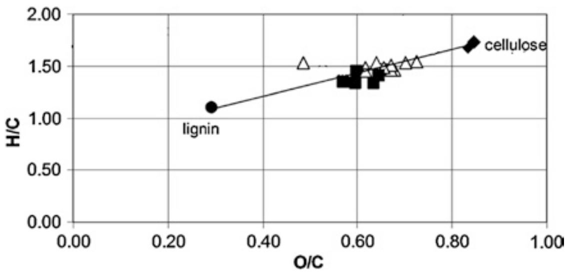


Fig. 2.8 Van Krevelen Plot of H/C against O/C for two types of biomass: woods *filled square*; herbaceous biomass, *triangle*. Values for lignin and cellulose are included (based on Jones et al. 2004)

a van Krevelen diagram [plot of H/C versus O/C atomic ratios (daf)]. The premise in this classification is that biomass feed-stocks that fall within clusters in the van Krevelen diagram will have similar properties, regardless of their category (waste, wood, etc.). This is shown in Fig. 2.8 where only organic (non-aqueous) H and O is included (i.e. wt% H from ultimate analysis is corrected for H in moisture, and O is calculated by difference using daf data). This type of information can be correlated to the high heating values.

This type of plot has now been used by a number of research groups and can be used in the prediction of other properties, such as Higher Heating Value, and potentially in predicting lignin, and other similar quantities for lignocellulosic biomass. However some other parameters such as volatile matter or fixed carbon correlate less well, because these parameters are strongly influenced by both heating rate and ash content/composition. There is added difficulty in that the analyses vary across different particle size fractions of the heterogeneous biomass samples. Variation is seen between leaf and stem as well as bark and the analyses are affected by time of harvest, geographic origin, fertilizer treatment and length of storage.

The three main components, namely cellulose, hemicellulose and lignin can be used as a method of classification. In this approach the classification is based on the approximation that these major components behave independently during pyrolysis and combustion, and that the biomass behaviour can be predicted based on knowledge of the pure component behaviour. This type of classification is shown in Fig. 2.9.

The woody and herbaceous species are not identified individually in Fig. 2.8 since no particular pattern is present. What it does show is that the concentrations of cellulose and hemicellulose are on average about equal and that species in the top right hand corner would have low lignin concentrations. This may be used as an indicator of the tendency to form low levels of smoke and of high reactivity. However, because of the influence of the minerals present this cannot be used as a reliably at present. Potassium has a considerable effect on the pyrolysis mechanism and the influence of that would have to be included in any complete prediction scheme. The uncatalysed process favours the formation of sugar-type monomers from the carbohydrates, but the presence of potassium changes the mechanism to one that involves ring cracking to give gases and the polymerisation to char. It is known that the addition of potassium to biomass pyrolysis aids the production of charcoal.

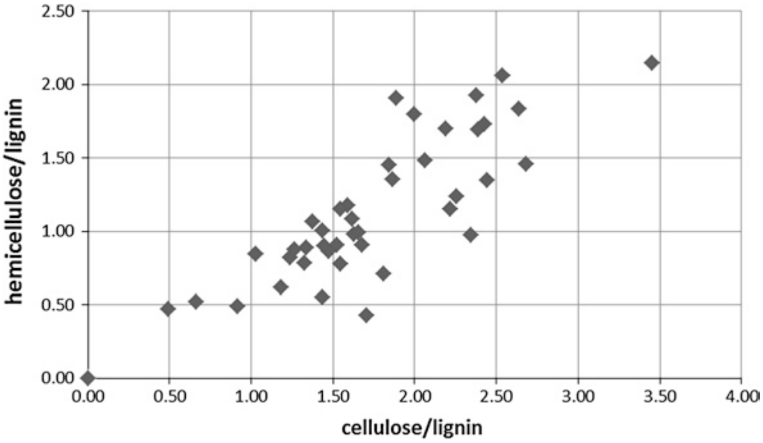


Fig. 2.9 Classification based on component composition for woody and herbaceous biomass samples (based on Jones et al. 2004)

2.5 Characterisation by TGA, PY-GC-MS and FTIR

Apart from chemical analysis it is possible to characterise a biomass by pyrolysis of a finely powdered sample in an inert gas stream or by combustion in air or oxygen. Laboratory scale thermogravimetric analysis (TGA) in air yields the burning profile, a mass loss trace. The first derivative of the weight loss curve gives characteristic temperatures for moisture loss, volatile loss, volatile ignition, char ignition and char burn-out. These methods were developed for coal but have been widely used for biomass in order to characterise the biomass in terms of ease of combustion and especially to determine the pyrolysis and char kinetics. This data can be obtained by slowly increasing the temperature or isothermally. Care has to be taken with these results because the upper temperature limit in a TGA is about 1,000 K which is below most char combustion conditions in many real combustion situations. If pyrolysis is undertaken in nitrogen or other inert gas with a heating rate of 5–40 K/s the mass loss curve produced shows the loss of water at about 100 °C and then a gradual loss due to pyrolysis only up to about a final temperature of 700 K when only carbon and ash remains and if oxygen is introduced then this can be burned out to leave ash. An example is shown in Fig. 2.10a. The derivative of this curve can be obtained to determine the kinetics and the difficulty is to decide at which point this is to be made.

In differential thermal analysis (DTA) the temperature differential between the sample and an inert reference is plotted giving a more sensitive indication of the reaction taking place. Figure 2.10b shows a differential thermal analysis of ‘synthetic biomass’, a mixture of cellulose (50 wt%), lignin (60 wt%), and xylan (20 wt%) which represents hemicellulose. In this plot a shoulder is visible on the main decomposition peak which is attributed to the hemicellulose decomposition,

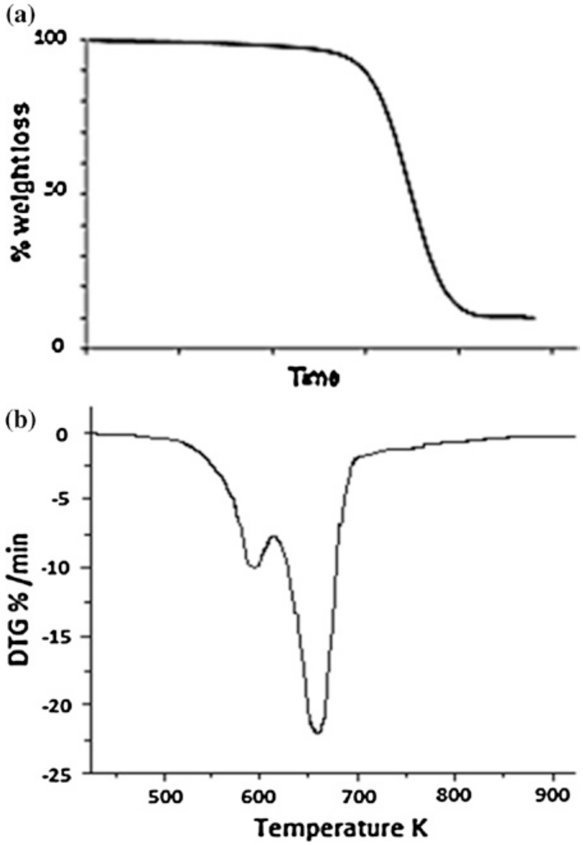


Fig. 2.10 **a** An example of a pyrolysis TGA curve showing percentage mass loss against time. **b** An example of differential thermal analysis of a 'synthetic biomass', a mixture of cellulose, lignin, and xylan which represents hemicellulose (based on Nowakowski et al. 2007)

while the main peak is mainly attributed to cellulose decomposition. Lignin decomposition gives rise to the broad underlying peak. Although these features are over emphasised in this synthetic mixture it shows the same general features shown my most biomass samples such as woods wheat straw, reed canary grass and switchgrass.

Another method of characterising biomass types is illustrated in Fig. 2.11 and consists of a pyrolysis unit coupled to a gas chromatograph with the products analysed by a mass spectrometer (Py-GC-MS). This technique uses an electrically heated coil or filament to pyrolyse a sample at a known temperature so that the products can be analysed. Considerable advances have been made in the analysis of biomass products but an extremely important but difficult area is in the analysis of high molecular weight tars (Kandiyoti et al. 2006). In some cases FTIR can be used in place of the mass spectrometer and is particularly useful in the case of nitrogen compounds for example Darvell et al. (2012).

This type of characterisation of biomass is useful for several reasons including understanding the reactivity of a biomass but also the PAH and smoke forming tendency. The cellulose decomposition products consist mainly of oxygenated

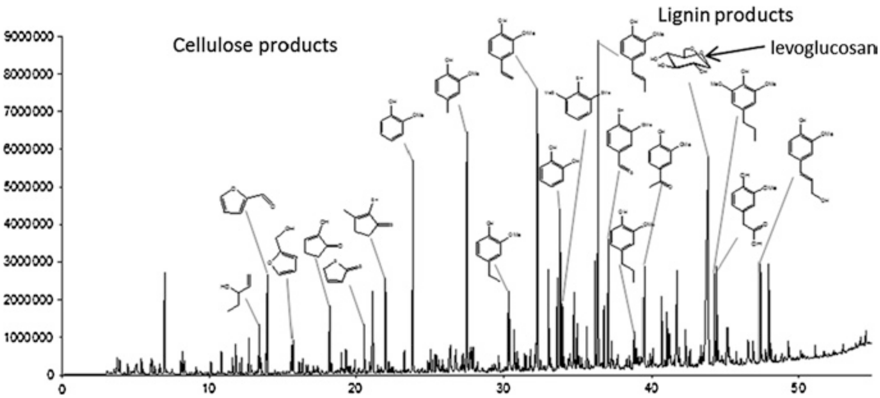


Fig. 2.11 Pyrolysis-GC-MS of pine wood with a pyrolysis temperature of 600 °C (*source* Dr. Emma Fitzpatrick)

products such as furfural and levoglucasan whilst the lignin components form largely aromatic compounds such as eugenol. The difference between pine, which is a softwood with high lignin content, and willow, which is a hardwood with a lower lignin content, is significant.

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